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An Analysis and Synthesis of Lunar Mascon Hypotheses

Based on Current Accumulated Lunar Knowledge

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ABSTRACT

Lunar mascons were first discovered from the tracking data of Lunar Orbiter V. Since their discovery, numerous hypothesis have been formulated to explain their origin and estimate their below-surface characteristics. As new data from Apollo missions are analyzed, various hypothesis have been altered, some new ones have been added, some old ones have been dropped. In this paper, the author summarizes the current factual knowledge on lunar mascons. The most recent hypothesis are then presented, and tested against the facts. Finally, a compromise hypothesis is synthesized from the most tenable points of the current hypothesis.

INTRODUCTION

In 1968, Muller and Sjogren processed the orbital tracking data of Lunar Orbiter V. A study of local accelerations on the spacecraft resulted in a gravipotential map of the lunar nearside which revealed very large mass concentrations beneath the center of all five nearside ringed maris (Imbrium, Serenitatis, Crisium, Nectaris, and Humorum). In addition, they were observed in the area between Sinus Aestuum and Sinus Medii, and Mare Orientale. From their interpretations, these mascons are large-scale high-density mass concentrations.

Since the discovery of mascons in 1968, additional lunar data has flooded in from Apollo orbital tracking data and from lunar surface experiments. First , the knowledge derived from this data, that is relevant to an understanding of all the characteristics of lunar mascons, will be presented. Then, the current competing hypothesis, which try to account for the genesis of the mascons, will be discussed and tested .

CHARACTERISTICS OF LUNAR MASCONS

Orbital tracking data has shown that all known mascons are located below ringed marias. This definite correlation between mascons and lunar surface features has forced scientists to account for both phenomena when devising hypothesis on the origin of mascons. The following facts, collected from numerous sources, describe the various surface characteristics of maria that are underlain by mascons.

(1) The mass concentrations on the moon are similar to the mass concentrations indicated by the earth's gravitational field in that the most marked departure from equilibrium are positive rather than negative. But lunar mascons are quite different from terrestrial mascons in that they are correlated (a) with topographic deficiencies rather than excesses, and (b) with presumably ancient geology, the ringed maria, rather than with recent geology(Kaula, 1969).

(2) Over the continental regions of the moon and the noncircular maria, gravity is constant within about 50 mgal (a unit of gravitational acceleration; one milligal = 0.001 cm./sec.^{2}). Over the circular maria, there are excesses of gravity up to 200 mgal (O'Keefe, 1968). Thus, while it is true that mascons always lie beneath maria; the converse, that maria are always underlain by mascons, is not true.

(3) Rilles are associated with mare-type material and are absent in the highlands. Most of them are located on the margins of the circular mare basins. More than 80% of the sinuous rilles lie on the margins of circular mare basins or craters with mare-type floors (Peale, et al., 1968). Five of the mascons underlie mare areas where sinuous rilles

are prevalent (Imbrium, Serentatis, Humorum, Aestuum-Medii, and Orientale) (Kane, 1969). Refer to Fig. 1.

(4) Maria cover one-sixth of the Moon's surface. A map of the mare areas on an equal area projection (Fig. 2) shows that they are distributed unevenly. Thirty percent of the near side is mare in contrast to only two percent on the far side. The great maria concentration on the near side lies mostly north of the equator, whereas the small mare areas of the far side lie mostly south of the equator. This north pole area and the adjacent northeast quadrant of the far side lack mare altogether, and a smaller empty area caps the south pole and covers the southern highlands of the near side. The maria tend to be concentrated along a crude global belt that approximated a great circle. (Stuart-Alexander and Howard, 1970).

(5) Maria occupy depressions, and their surface elevations, though variable, average lower than the terra. Some deep depressions, however, contain no mare. Many maria occupy large circular basins but the largest mare area is the irregular Oceanus Procellarum which is not circumscribed by ring structures (Fig. 2). Smaller mare patches occur in smaller craters and irregular depressions. Superposition relations indicate that all mare surfaces are relatively young compared to other lunar features even though their absolute ages may be great. These relations include the filling and embayment of relatively fresh features by mare material and the youthfulness of all craters that are superposed on maria. (Stuart-Alexander and Howard, 1970).

(6) Most major maria occupy large circular basins, but not all basins contain mare (Fig. 2). All basins wider than 500km and most basins wider than 400km contain some mare, whereas two-thirds of those between

300 and 400 km contain none. However, the quality of mare is not proportionally distributed among like-sized basins: nearly all near-side basins within the mare belt are flooded whereas similar basins outside the belt and on the far side are only partially flooded or unflooded. Most of the mare areas on the near side are in circular basins or near them. The mare material of Oceanus Procellarum is continuous with that of the Imbrium basin, but the vast area of Procell-arum suggests it is not related to the Imbrium basin.

Among the circular basins, the partly filled basins show a prefer-ence for mare to be located first centrally in the inner basin and second in concentric valleys between mountain rings, suggesting this was the order of filling of the more completely flooded basins also. The initial stage of mare flooding in smaller craters such as Humboldt is generally along the outer and apparently lowest part of the crater floor. Thus mare is emplaced preferentially in certain structural positions of craters and basins, and these positions coincide with the lowest depressions. (Stuart-Alexander and Howard, 1970).

(7) Evidence of sinking is furnished by the inward inclination of craters on the mare borders, and especially by the ring-fault around Mare Humorum, with the downthrown side toward the mare. (O'Keefe, 1968)

(8) There is an absence of appreciable blowout associated with the ringed maria (Kaula, 1969).

(9) Unusually long reverberations were recorded from two lunar impacts by a seismic station installed on the lunar surface by the Apollo 12 astronauts. Seismic data from these impacts suggest that the lunar mare in the region of the Apollo 12 landing site consists of material with very low seismic velocities near the surface; that is, absorption of seismic waves is extremely low relative to typical continental

crustal materials on earth.(Latham et al., 1970).

LUNAR MASCON HYPOTHESES

Immediately following Muller and Sjogren's discovery of mascons, innumerable hypotheses were formulated to account for their genesis. One point that they all had in common was the idea that the maria basins were carved out by asteroidal-sized bodies early in the moon's history. Apart from this point, interpretations of maria features differ widely in accounting for the subsurface mascons.

(I) -- LAVA LAKE HYPOTHESIS

One of the first hypotheses (Baldwin, 1968) dealt only with the origin of Mare Imbrium, but could easily be generalized to fit all maria-containing mascons. The following sequence of events was postulated:

"1) Mare Imbrium was formed by a giant impact.
2) Its initial depth was approximately 50 km.
3) It was formed dry – that is, not lava-filled.
4) It began to distort isostatically, rapidly at first, then more slowly.
5) Before the basin disappeared, lavas from the body of the moon rose and began to selectively fill the low spots. There were many flows, not just one.
6) These lavas were substantially denser than other surface rocks. The outer portions of some flows were basalt-like (Turkevich et al., 1968). Basalt has a bulk density of about 2.95.
7) Tension cracks (rilles) on the periphery and compression features (wrinkle ridges) in the interior of Mare Imbrium and the great depth of the present surface of the central crater relative to the lava-covered surroundings are evidence that subsidence and compaction have occurred.
8) If the prelava surface of the moon as exemplified by the continental regions is composed substantially of acidic materials, then it is probable that the density of the lava after solidification is about 0.4 g/cm^3 greater than that of the continental rock type.
9) Pike has shown that even the very young craters like Tycho are being modified isostatically so presumably the interior of the moon is still very hot (Pike, 1968).

10) If sufficient lava is released into a giant crater it will continually depress the crater bottom due to the increased load of high-density matter. The original bottom of the crater may then sink back to its original position or even deeper into the moon. The cold solidified lava probably would be denser than the hot subsurface materials beneath the crater.
11) By this mechanism, a dense lens of material could be formed that was centered in the crater and capable of yielding the gravitational effects measured.
12) Some dense matter from the meteorite might also remain in the pit and would add to this effect. The tiny Arizona meteorite crater was formed by a rather low-velocity object, and a small amount of nickel-iron was found by drilling below the crater floor." (Baldwin, 1968)

The above sequence of events was supported by the work of R. J. Pike Jr. who stated that all craters are of the form defined by the equation

". . .

$$R_i = 0.155 D_r^{0.95}$$
$$R_e = 0.042 D_r^{0.98}$$

where R_i is the internal relief from crater rim to maximum depth; D_r is the rim to rim diameter; and R_e is the height of the rim above ground level. The diameter of the Mare Imbrium central crater is 676 km, and from this we find that R_i = 76 km, R_e = 25 km, and hence the initial depth of Mare Imbrium below ground level was about 51 km."((Baldwin, 1968), from (Pike, 1968))

These calculations were consistent with the original observations of Muller and Sjogren. They measured the excess mass of Mare Imbrium as 20 x 10^{-6} lunar masses for a depth of 50 km. Baldwin, assuming that the internal contour of the crater was parabolic, expressed the excess mass in the crater as $0.392\Delta p r^2 h$, where $\underline{\Delta\ p}$ is the excess of density (0.4); $\underline{r}$ is the radius of the crater (3.38 x 10^7 cm); and $\underline{h}$ is the maximum depth below ground level (82 km). This value for the bottom of the high-density lens is in good agreement with the value of 50 km for the depth of the mascon that was suggested by the Orbiter observations. The concentration of excess mass toward the center of Mare Imbrium in this model is also consistent with the gravitational measures.

With small modifications, this hypothesis was further supported more than a year later by J. A. Wood (Wood et al., 1970). His examination of the Apollo 11 rock fragments showed that 61 of the 1676 rocks examined were anorthosites. They were markedly different in composition, color, and specific gravity from the mare basalts and soil breccias found at Tranquility Base. Wood suggests that the anorthosites are samples of highlands material because of compositional similarity to Tycho ejecta analyzed by Surveyor VII. He proposes a lunar structural model (Fig. 3) in which a 25 km anorthosite crust, produced by magmatic fractionation, floats on denser gabbro. Where early major impacts punched through the crust, basaltic lava welled up to equilibrium surface levels and solidified forming maria. Mascons are viewed as minor deviations from lunar isostasy. They were formed as follows:

> "Basic lavas contract on crystallization and increase in density by about 10% (Clark, 1966), so the equilibrium surface of a lava lake penetrating the lunar crust would stand about 2 km lower after crystallization than before (Fig. 3). The important point to note is that, after a lava-filled mare solidified and dropped to level II (a state of hydrostatic equilibrium), any additional lava that could find its way up to the surface would be capable of refilling the mare basin to level I. Level I would continue to be the free liquid surface in hydrostatic equilibrium with subcrustal magma, in spite of the (solid) equilibrium nature of level II.
>
> If a liquid zone underlay the solidified mare, addition of such an overburden would probably drive the whole system down to a new position of overall equilibrium. If the mare was supported beneath, however, extrusion of lavas from surrounding subcrustal zones onto the mare surface would constitute a genuine addition of mass to that area of the moon and would give rise to a positive gravity anomaly. Complete filling of the zone between level I and level II with lava of density 3.3 g/cm^3 (solidified), which is hydrostatically possible, would give rise to a gravity anomaly of 276 mgal. Since the observed gravity anomalies are little more than half this great (Muller and Sjogren, 1968), it is not necessary to postulate 100% efficiency in lava overfilling or in the support of overfilled maria by the material underlying them." (Wood, 1968)

Thanks to the Apollo 11 data, Baldwin's lava lake hypothesis has more quantitative substance than originally.

Baldwin accounts for the lack of mascons in other basins by stating that lava never filled these basins after isostatic adjustment took place. The fact that Baldwin allows for lava infilling of mascon basins only AFTER isostatic adjustment has taken place is consistent with data presented earlier in this report which states that maria-basin infilling took place much later than the formation of the original basin. The Wood explanation is not necessarily inconsistent, because the most recent surface lava flow may well have occurred much later than the formation of the original basin.

Baldwin's hypothesis does not rule out the slight possibility that meteorite material buried within the great crater does contribute to the observed mass concentrations, but it does suggest that a high-density lava infilling, aided by isostatic adjustments which caused the crater bottom to sink, can, in itself, explain the major positive anomalies of the lunar gravimetric map.

(II) -- METEORITE HYPOTHESIS

At the same time that Baldwin forwarded his hypothesis, J. C. Stipe had an alternate proposal (Stipe, 1968). His investigations allowed a calculation to be made of the size and depth of the mascons in terms of the size of the mare formed by low-velocity impact of an iron meteorite. From his investigations he suggests that the lava-filled maria were formed when very large iron meteorites struck the surface of the moon at a velocity so low that there was no immediate fracture of the object. The impact produced a very large crater, and the object penetrated to such a depth that deep material was melted by pressure release (Ronca, 1966) and flowed to the surface to fill the crater. The interior of the moon must have been solid when these events occurred, because otherwise the dense iron meteorite would have sunk into the molten material. Each mare is formed by one large iron object, and this dense object under the mare is the mascon discovered by Miller and Sjogren.

The principal lunar evidence in favor of low velocity impacts is (i) the absence of appreciable blowout associated with the ringed maria, and (ii) the distinct ellipticity of the maria Imbrium, Serenetatis, and Crisium (Kaula, 1969).

Uray supports the meteorite hypothesis because he feels that;

> "It is difficult to devise a lunar history which provides the low temperature required to account for the lack of isostasy and the low electrical conductivity, and at the same time" … account for …"melting processes required to produce the basaltic material on the surface of the moon." (Urey, 1968)

(III) -- WATER HYPOTHESIS

In late 1969, J. J. Gilvarry explained the origin of mascons in terms of a primordial atmosphere and hydrosphere of the moon lasting approximately one billion years from the moon's origin 4.5 billion years ago. On this basis:

> "… the mascons arose in four steps: (1) excavation of a large crater by meteorite impact at a time close to the moon's origin, (2) subsequent isostatic adjustment of its rim and true floor, (3) rigidification of the crater and extensive deposition of sedi ments in its interior while an atmosphere and hydrosphere existed, and (4) eventual dessication of the sediments in the floor when the atmosphere and hydrosphere vanished. Rigidification of the crater (within a time about 1 m. y. after the moon's origin) prior to the main deposition of the sediments implies that the mascon load is supported by the strength of the underlying rock to produce a positive gravitational anomaly (independently of sediment density). The same history of the hydrosphere explains the presence of negative mascons in the irregular maria as a consequence of low sedimentation in these areas." (Gilvarry, 1970)

The formation of the primordial lunar atmosphere and hydrosphere and its consequent loss is postulated to have occurred in the same manner and by the same mechanism as in the case of the earth; that is, the atmosphere and hydrosphere were created by exudation of volatiles from the solid interior, and lost by gas heating to a speed on excess of the lunar escape velocity. Gilvarry circumvents the current thinking that the moon was formed in a cold state through accretion, by stating that a relatively short phase of moderate internal heating by the energy of gravitational accretion or of radioactive decay (possibly involving extinct nuclides of short lifetime) occurred to volatilize the condensates and degas the lunar interior.

Gilvarry assumes that this thermal event was of sufficient intensity so that the moon could react at depth by plastic flow to applied stress differences for a time 'τ_i' reckoned from the time of its formation(about 4.5 billion years ago). Hence, any mass imbalance of sufficiently large scale on the lunar surface would be compensated isostatically if it were produced within the time period τ_i. Isostatic compensation is considered impossible even for large scale features formed after time τ_i.

The lunar maria are among the oldest features on the lunar surface, because of the heavily eroded appearance of the mountains forming the crater rims (Baldwin, 1963), Gilvarry assumes that they were all formed within a time 't', such that $t \ll \tau_i$. A cross-section through a typical circular mare at the time of creation by meteor impact is shown in Fig.4, panel A. At a time $t \approx \tau_i$ later, the crater would have assumed the isostatically compensated form of panel B. The upward displacement of the 'fiducial stratum' (corresponding to the earth's mantle) is the same as that observed by seismometers on earth for the Mohorovicic discontinuity under the floors of the oceans.

Gilvarry determined theoretically τ_i using Haskell's equation (Haskell, 1937), assuming that the earth's asthenospheric viscosity is the same as the moon's. The result indicated $\tau_i \approx 10^5$ years. During this period, volatiles (H_2O) degassed from the lunar interior.

The time 'τ_r' after the formation of the moon is assumed to satisfy $\tau_r \gg \tau_i$, so that significant amounts of water have been released.

By the time τ_r, local pools of water would have collected to form a continuous sheet averaging 2 km thick, drowning all the lowlands and parts of the highlands.

Gilvarry himself has again computed the time 'τ_e' for the thermal escape of the hydrosphere and atmosphere by scaling the numbers of the corresponding molecules on the earth according to the volumes of these two bodies to estimate the initial amounts. On this basis, he obtains τ_e = 1 b. y."(with some uncertainty in the numerical coefficient)".
For times satisfying $t \gg \tau_e$, the cross-section of panel D indicates that all the water has escaped and that the bottom of the mare has filled with sediments washed in from the highlands.

According to his theory, then, the sediments in the floor of a circular mare represent an added mass transported a long distance from the highlands by water flowing on the surface or in rivers after rainfall. Further, in view of the time periods involved, he believes that the main deposition of sediments took place after isostatic equilibrium of the true mare floor was reached. Thus, the sediments create a positive gravity anomaly. He further states that the approximate isostatic equilibrium of the highlands was not disturbed by the erosional processes because of the thinness of the layer eroded from the relatively large area represented by the lunar uplands.

Gilvarry uses Fig. 5 to illustrate evidence in support of his ideas.

> "The implication of the variation of surface depths and the distribution of dark material is that the dwindling waters finally pocketed in Mare Imbrium (Gilvarry, 1964, 1965). Mare Serenetatis is higher in elevation than is Imbrium, in

accordance with the suggestion in Fig. 5 that the former drained into the latter. Further, a channel of the correct depth connects these two maria where they are contiguous. In the general neighborhood of Mare Nectaris, the lowest area is the floor of the mare, which is in agreement with the appearance of the dark area as a region cut off from drainage into the adjacent Mare Tranquillitatis. Moreover, the intensity of the dark coloration increases along an arcuate locus extending from Mare Nectaris through Mare Tranquillitatis and Serenetatis to Mare Imbrium, in the general direction of the gradient of gravity along the arc. On this basis, the strength of a positive mascon should increase with the depth of the original meteoritic crater and the extent of the lunar surface that drained into it." (Gilvarry, 1970)

Gilvarry accounts for negative anomalies by predicting that at time $t \approx \tau_i$, when isostatic adjustment ceased, the floor of the mare was downwarped to compensate for the loading of water. This would create a negative anomaly after the water had escaped. In most basins, this negative anomaly was erased and became positive as a result of heavy sedimentation. However, basins that still have negative anomalies are characterized by having irregular maria shallower than circular basins. Further, the centers of the irregular maria lie at long reaches over areas of low slope to the lunar highlands: locations conducive to low sedimentation. Consequently, the negative anomalies were not erased and remain today.

Support for Gilvarry's hypothesis comes from E. M. Shoemaker (Showmaker et al., 1968) who identified extensive flows on the rim flank and in the interior of the crater Tycho, which strongly suggested to them transport by a fluid, with water being the best possibility. In addition, channels with levees suggestive of mature terrestrial rivers were found. Finally, almost every local closed depression above a certain size in the vicinity of Tycho displays a flat floor covered with a dark material obviously transported to the site and indistinguishable from that appearing in the maria. They even show branching grooves resembling the cracks and fissures formed by contraction and dessication of the beds of dry lakes on the earth.

DISCUSSION

None of the three hypotheses accounts for all of the facts listed earlier in this report. Also, objections can be raised against each of the hypotheses and their proponent's interpretations of lunar features, or their failure to account for certain surface features.

The lava lake hypothesis makes no attempt to account for the sinuous rilles and their concentration around the rims of maria basins. Although the explanation most consistent with the hypothesis would be that the rilles were produced by volcanic ash flows or lava drainage channels, the possibility is disputed by S. J. Peale (Peale et al., 1968). He states there are strong morphological arguments AGAINST the igneous origin of rilles. W.M. Kaula has also forwarded arguments against the lava lake hypothesis (Kaula, 1969). He argues that there are no mechanisms to account for the rising of basalt through a lower density crust, except by excess internal pressure. Baldwin and O'Keefe suggested that this pressure is generated dynamically, as on earth, by convection, and that the greatest eruptions of lava have occurred on the ringed maria because they are the places where the crust is weakest.((Baldwin, 1968),(O'Keefe, 1968)). But Kaula retaliates that it is highly improbable that such an active lunar interior would produce excesses coinciding so closely with ancient surface features; also, the model is inconsistent with the evidence of low internal temperatures inferred from the slight effect of the moon on transients in the solar wind.

Turning to the meteorite hypothesis, Kaula (1969) also attacks this model. A difficulty associated with the hypothesis is that the circumstances of impacts with large bodies have not been worked out;

simple scaled extrapolations from available data on nuclear explosions indicate that throwout mass is a factor of 20 times infall mass at the escape velocity of the moon. This blowout, Kaula concedes, is undoubtedly an overestimate, but he doesn't know how much of an overestimate. In any case, a meteorite large enough to leave a mascon-producing remnant after impact, seems unlikely, especially in view of the fact that there is an absence of appreciable blowout associated with the ringed maria.

Relentlessly, Kaula goes on to attack the water hypothesis on the basis that the moon could not have outgassed enough water fast enough to erode and deposit the 1 to 2 km. of excess material necessary to produce a positive anomaly. Gilvarry assumes that the moon was as efficient in outgassing as the earth, which implies a hot interior, perhaps too hot to permit the crust to cool off at depth in time to support the mass excesses necessarily laid down before the atmosphere escaped.

CONCLUSION

Undoubtedly, the true answer to the controversy will probably include the most tenable parts of each model:

- The strongest point in the lava hypothesis comes from the Apollo 11 samples, which contained anorthosite and basalts.
- The strongest point in the meteorite model is the widely held belief that only a large meteorite could have carved out the circular maria basins.
- The strongest point in the water hypothesis is the undeniable identification of sinuous rilles having structures identical with terrestial river systems.

In concluding, I can only state that the present amount and type of lunar data cannot conclusively resolve the mascon controversy. The final solution can only be attained after further lunar surface exploration.

ACKNOWLEDGEMENTS

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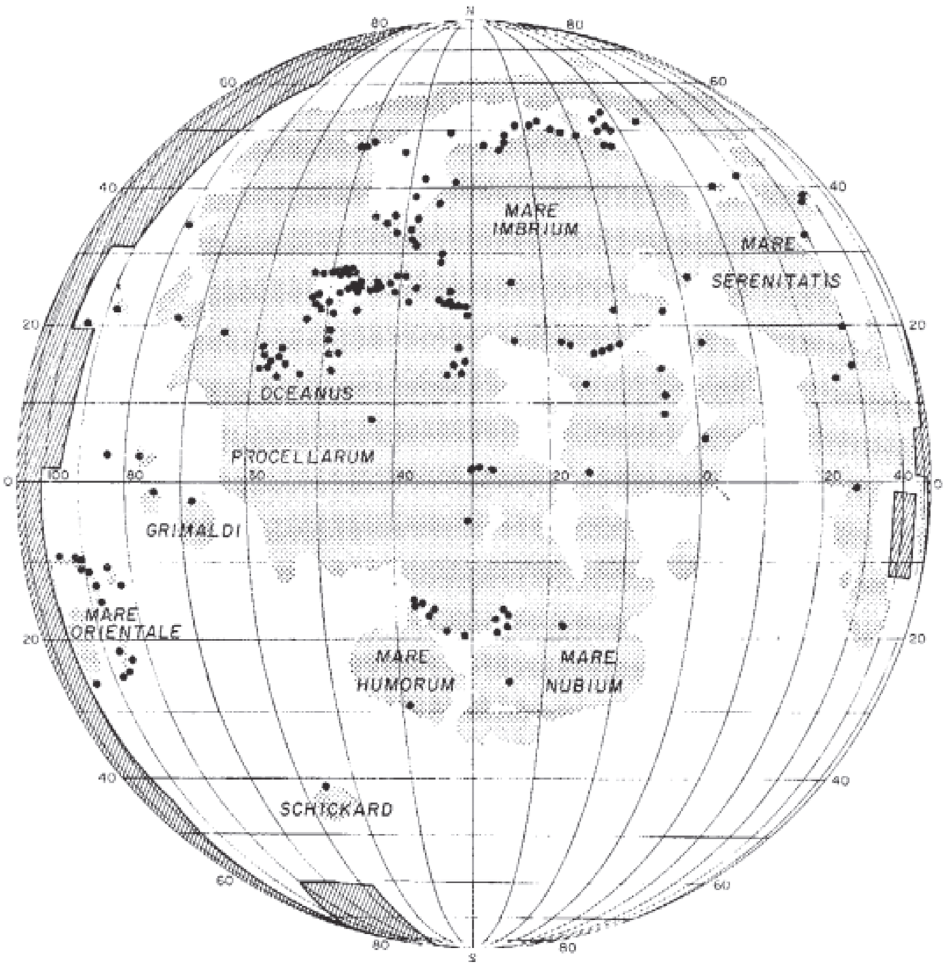

Fig. 1 Distribution of sinuous rilles based on the Lunar Orbiter IV high-resolution photographs, frames 59 to 196, which cover roughly three-quarters of the visible face of the Moon (from about 50° E to 100º W longitude). The face of the Moon shown is that seen by an observer situated 30° west of the Earth-Moon line. The hatched area indicates regions of poor or nonexistent coverage. Each rille, regardless of size, is designated by a dot located approximately at its source. A frame consists of three 20 inch x 24 inch contact prints covering a field of about 260 by 340 km with a resolution of about 100 m. The camera axis was nearly parallel to the lunar surface normal, and the incident angle of the sunlight was between 70° to 75°, providing good aspect and illumination for the detection of low relief.

(Peale et al., 1968)

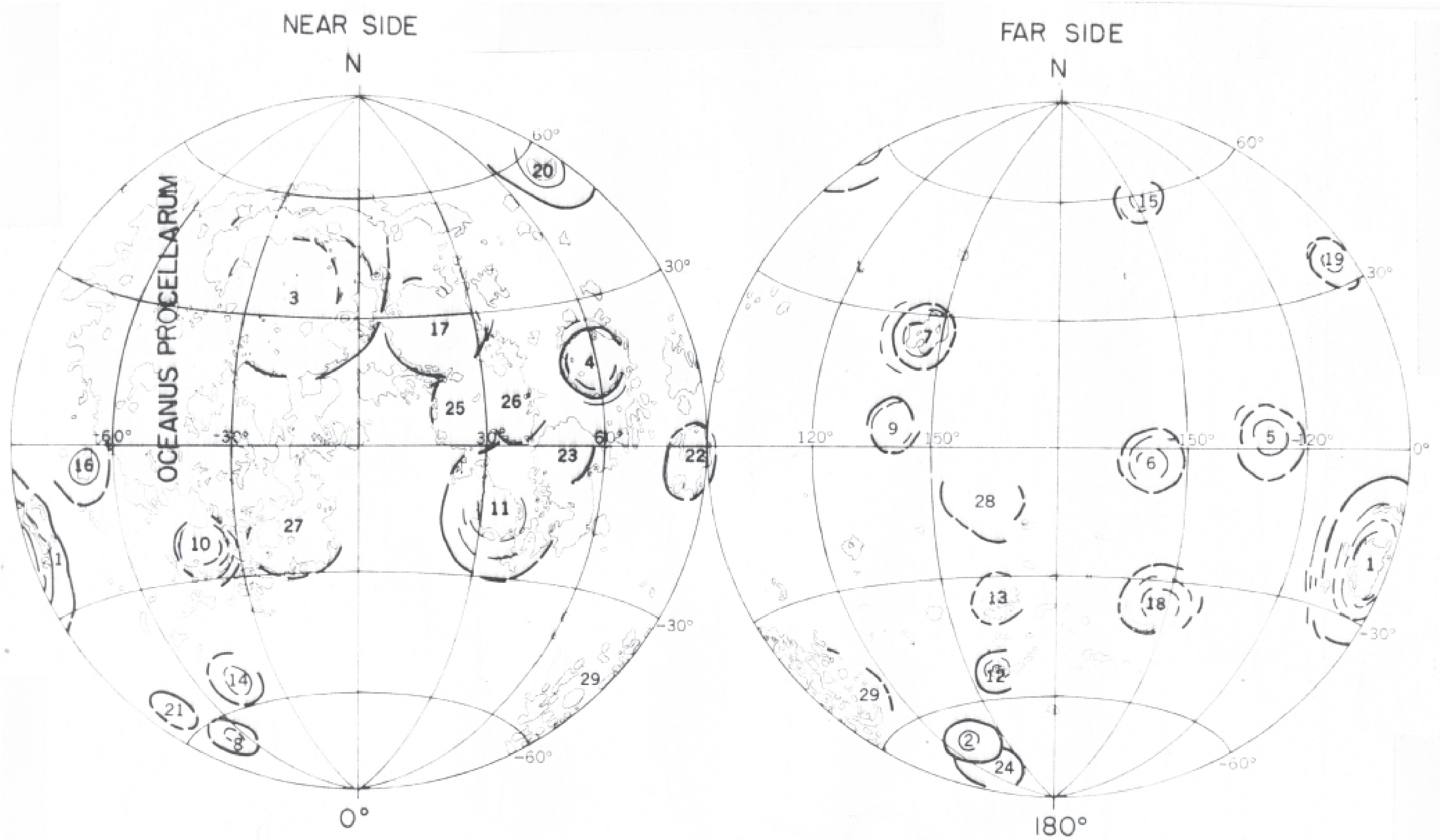

Fig. 2. Distribution of maria and large circular basins, Lambert equal-area projection; basins 300 km or more in diameter. Mare areas are shaded. Basins numbered as in Table I. The highest mountain ring of each basin is shown by a heavy line; secondary mountain rings are shown by light lines. Location and size of far-side features are taken from ACIC provisional Lunar Farside Chart (LFC-1), 2nd edition, 1968.

(Stuart-Alexander and Howard, 1970)

TABLE I

CIRCULAR BASINS[a]

Name	Location		Representative Lunar Orbiter photos	Diameter (km)	Age Group
	Longitude	Latitude			
1. Orientale	−95	−20	IV M-187	900	
2. —	130	−70	IV M-4	300	IV
3. Imbrium	−19	37	IV M-115, M-134	1250	
4. Crisium	59	17	IV M-60	450	
5. —	−129	3	V M-24, M-26	490	
6. —	−158	−3	I M-30, M-38	450	
7. Moscoviense	145	25	V M-103, M-124	460	III
8. Bailly	−69	−67	IV M-179	310	
9. —	141	5	I M-116, M-117	330	
10. Humorum	−39	−24	IV M-137	430	
11. Nectaris	34	−16	IV M-71, M-84	840	
12. —	160	−53	V M-65	300	
13. —	165	−35	II M-75	370	
14. near Schiller	−45	−34	IV M-142	350	
15. —	−148	58	V M-29	300	
16. Grimaldi	−68	−5	IV M-161	430	II
17. Serenitatis	19	26	IV M-91, M-97	680	
18. —	−153	−35	V M-26, M-30	480	
19. —	−98	35	IV M-189	320	
20. Humboltanium	81	58	IV M-23	640	
21. Pingré	−79	−56	IV M-180	300	
22. Smythii	84	−3	IV M-12, M-17	370	
23. Fecunditatis	51	−3	IV M-52	480	
24. —	130	−78	IV M-94	370	
25. W. Tranquillitatis	27	9	IV M-72, M-84	550	I
26. E. Tranquillitatis	38	11	IV M-72, M-84	500	
27. Nubium	−17	−19	IV M-120	750	
28. —	162	−11	II M-75	480	
29. Australe	90	−45	IV M-9, M-106	900	

[a] Listed in approximate order of increasing age, based on degree of modification. Diameters and locations are subject to revision. Identification of some basins included in age group I is questionable. Photographs referred to are of the Lunar Orbiter project of the National Aeronautics and Space Adminstration. The roman numerals refer to the number of the Lunar Orbiter Flight, the M refers to moderate resolution photograph, and the arabic numbers to the frame number.

(Stuart-Alexander and Howard, 1970)

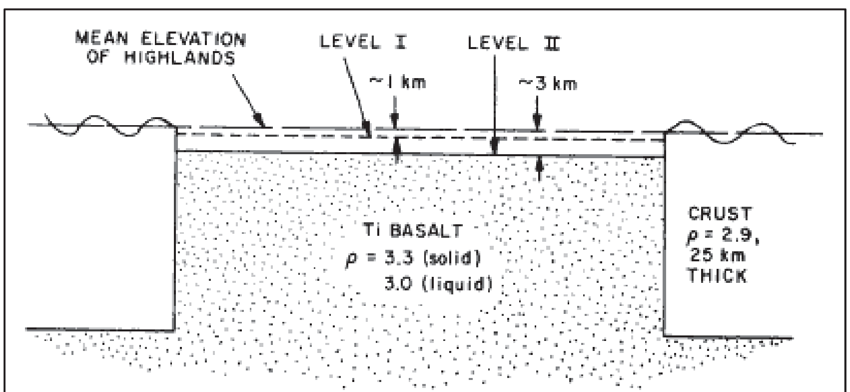

Fig. 3. Schematic representation of a lunar crustal section, showing equilibrium surface levels for mare basalt when molten (level I) and when solid (level II).

(Wood, 1968)

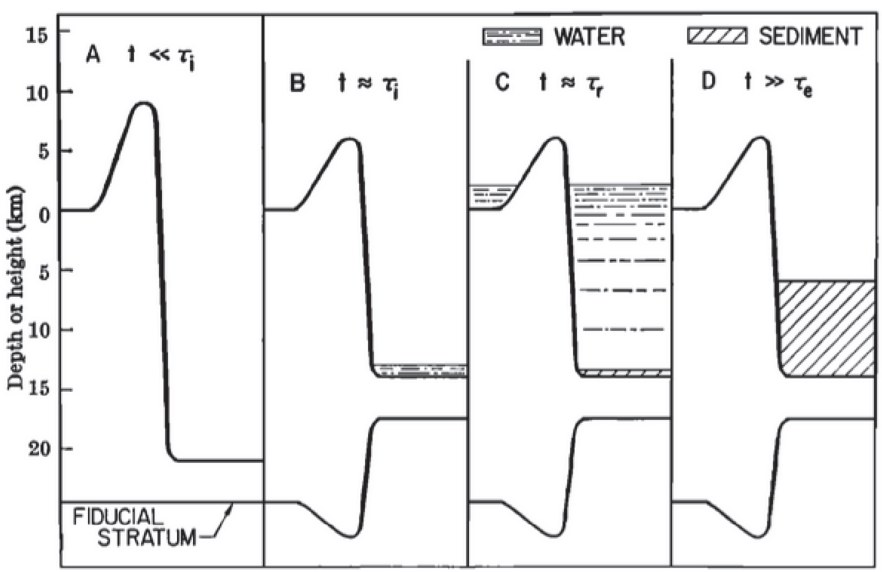

Fig. 4. Schematic representation of the formation of a positive mascon. In panel *A*, an uncompensated crater as formed by meteoritic impact is shown. Panel *B* represents the same crater after isostatic adjustment and containing some water. Panel *C* shows the same crater filled completely with water and containing some sediment. The final form after escape of the water is depicted in panel *D*, with the load of sediments on the isostatically compensated floor of the crater producing a positive mascon. The vertical dimensions correspond approximately to Mare Imbrium.

(Gilvarry, 1970)

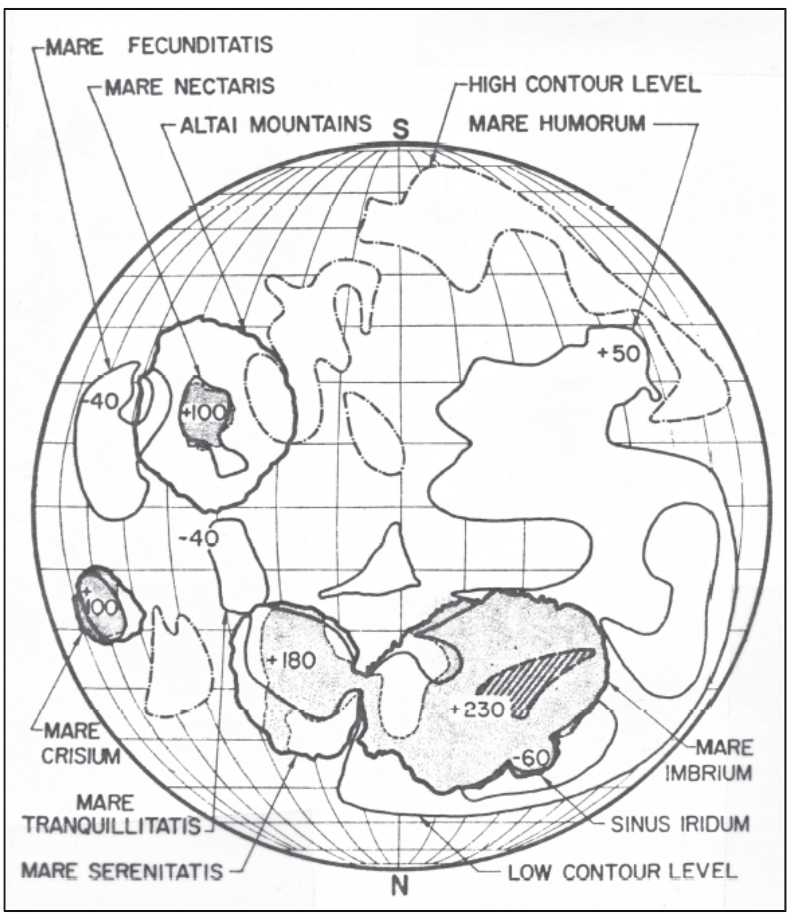

Fig. 5 Locations of the most prominent positive and negative mascons on the near face of the moon, indicated by numbers specifying the strength of the anomaly in milligals. Contour lines corresponding to one-thousandth of the lunar radius (roughly 2 km) below and above the mean sphere are shown (solid and dot-dashed, respectively) as constructed from the lunar contour map of Baldwin (Baldwin, 1961). The line of the greatest depth (6 km) below the mean sphere appears dashed, with the interior cross-hatched. The outlines of the rim are shown by heavy irregular lines for the circular maria for comparison with the content (shown stippled) of the dark Mascons in the floor.

(Gilvarry, 1970)

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